Intra-seasonal mid- and high-latitude circulation fluctuations forced by and coherent with tropical heating: Predictability and prediction

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The MJO Cycle Forcing of the North Atlantic Circulation: Intervention Experiments with the Community Earth System Model. *Accepted to the Journal of the Atmospheric Sciences.*

Goals

(1) Explore the mechanisms by which the MJO heating affects the intraseasonal variability of the NAO through mechanistic GCM experiments.

(2) Determine the systematic response of the extra-tropical atmosphere to MJO heating using a model and experimental set up in which realistic mid-latitude noise is present.

Defining a mechanistic MJO response in the context of a full coupled GCM

The MJO heating is *not* a single localized source but a cycle in both space and time, consisting of negative and positive anomalies.

From a linear point of view, both the heating and cooling at one particular time may be thought of as sources for wave trains.

The remote response at any point some time later will involve the sum of these wave trains, each having traveled a different distance to reach the given point and thus in a different phase of its life cycle.

The dependence of the linear response to time-dependent forcing on the entire past history of the forcing is well known in classical electrodynamics

Defining a mechanistic MJO response in the context of a full coupled GCM

Control CESM runs: 48 Oct-Mar seasonal runs

For each control run*, a parallel heating run* was made from the same IC, with a specified MJO heating added at each time step to the temperature tendency in the model. The evolution of the ***specified additional heating is identical*** in each of the 48 heating simulations.

The full set of model parameterizations still operates, so that, for example, the added heating is able to induce added vertical motion which may induce further condensation, latent heat release, and changes in the associated cloudiness and radiation.

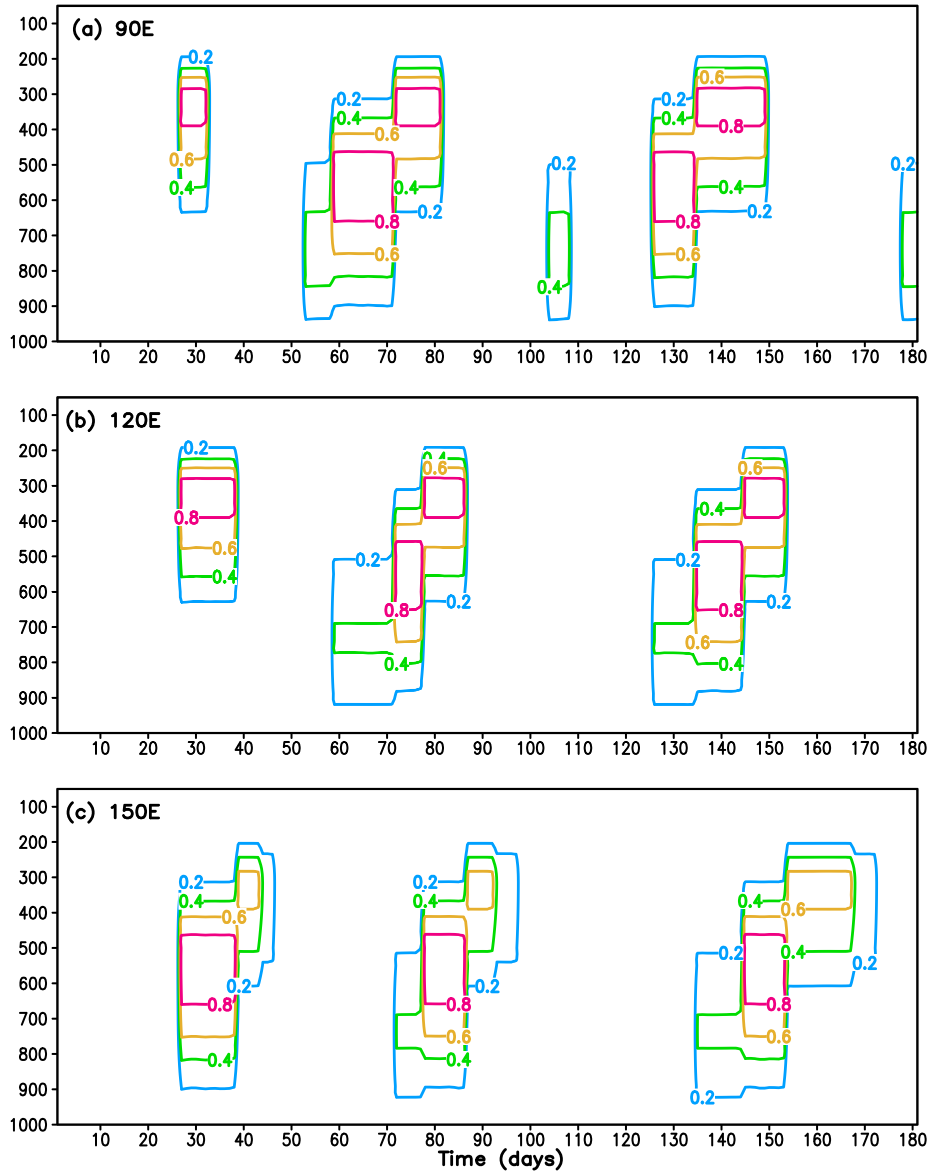
The Specified Additional MJO heating

- The three-dimensional heating is based on TRMM radar observations (shallow to deep convection)
- The observed climatology of heating for each month/day for each MJO phase is taken into account (expected timing and amplitude)
- The evolution of the additional heating spans slightly more than 3 full cycles of the MJO, starting the first cycle with phase 5 (active in Indian Ocean) on 27 October and ending the last cycle with phase 6 (active in W. Pacific) on 15 April, for a total of 24 total phases

Temperature tendency due to additional heating at various longitudes (ave. 25S – 25N) as a function of time (abscissa) and pressure (ordinate)

Day 1 corresponds to 2 Oct.

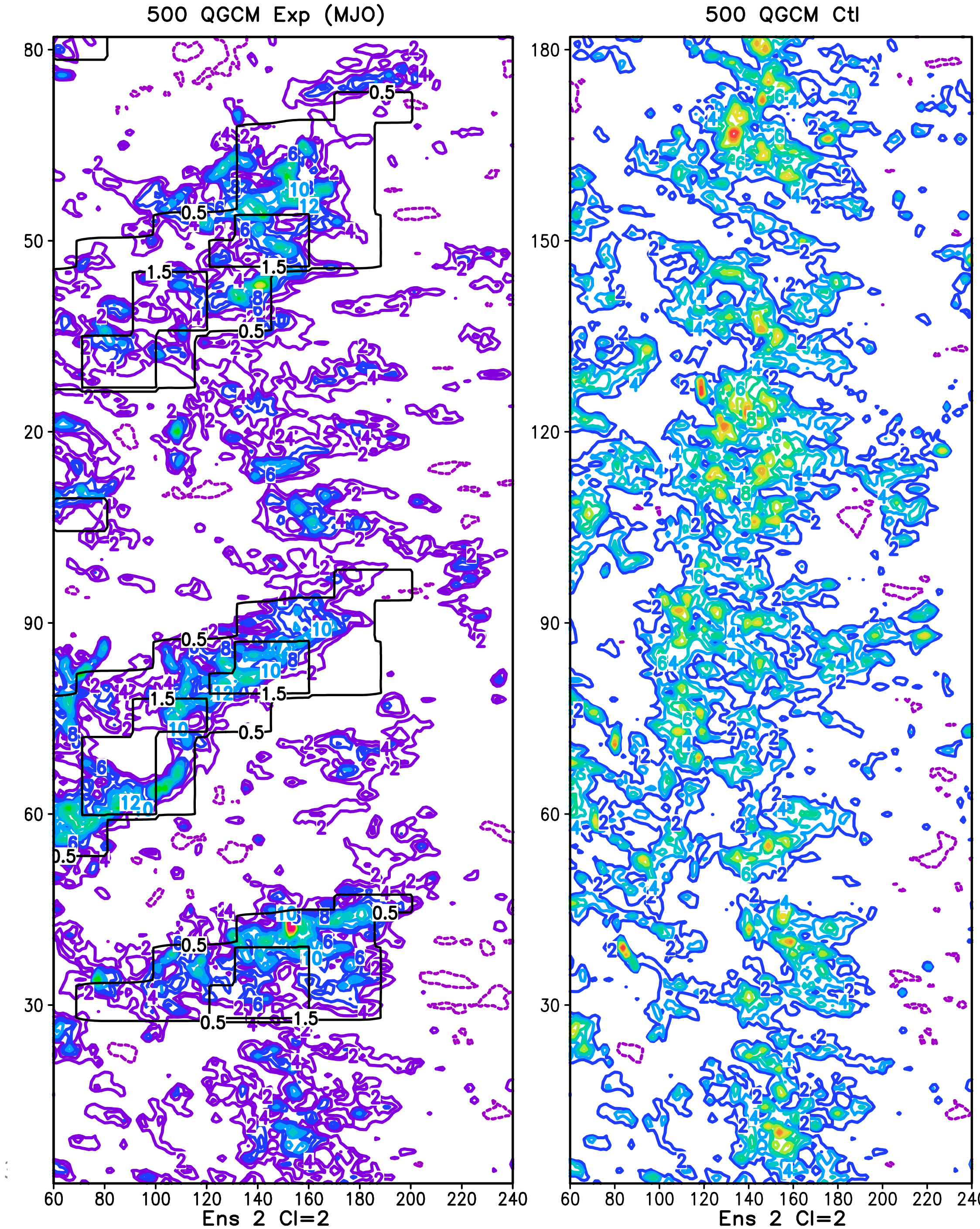
Pressure in hPa



Temperature tendency due to all diabatic heating processes (including additional heating) from a **single ensemble member** at 500 hPa (colored, 10S-10N, interval 2 K/day) and additional heating alone (black, interval 0.5 K/day)

Heating run (left), corresponding Control run (right)

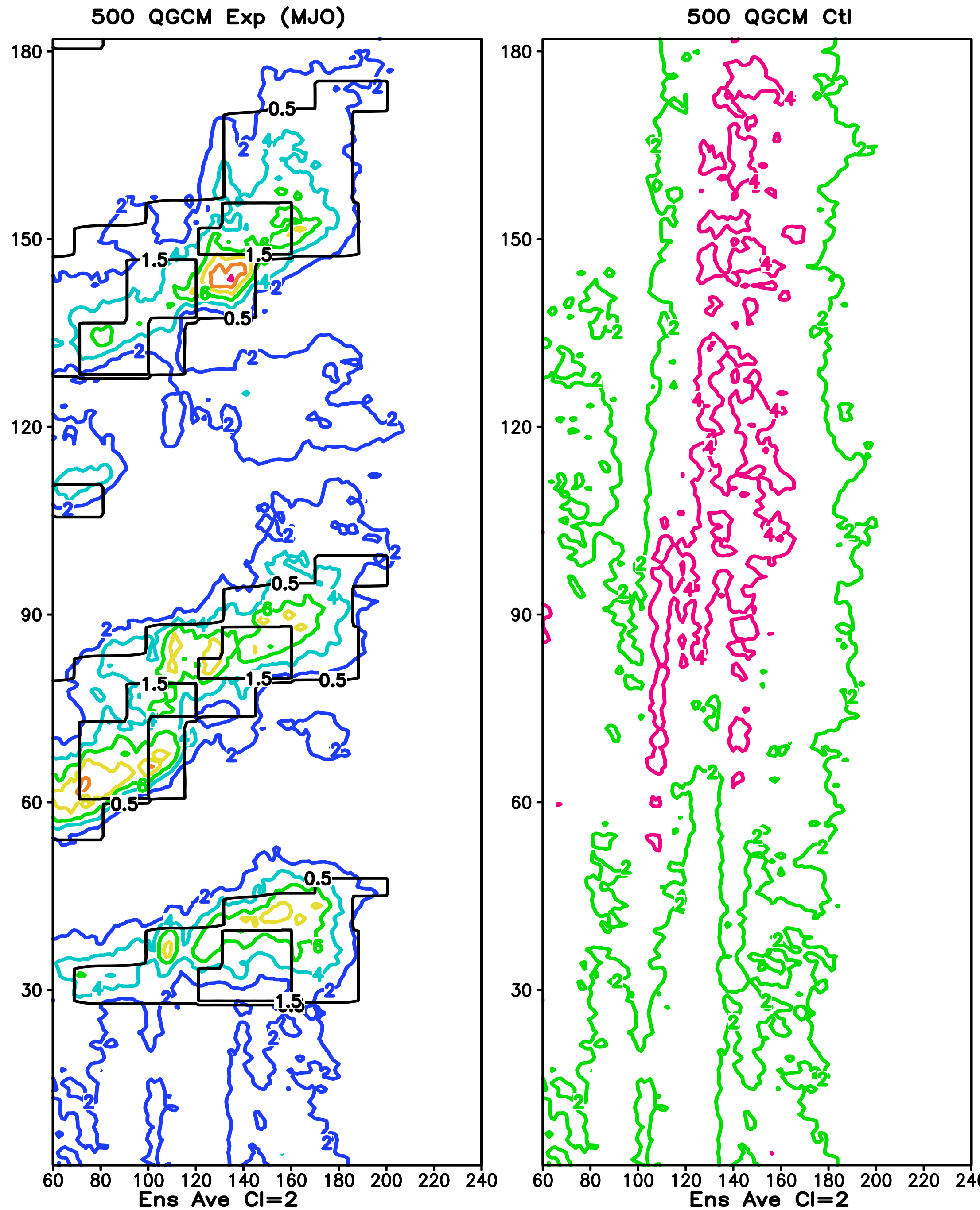
Forecast time (ordinate, 1 to 181 days beginning 2 Oct.) vs. longitude (abscissa, in degrees, 60E-240E)



Temperature tendency due to all diabatic heating processes (including the additional heating) from the **ensemble average** at 500 hPa (colored, 10S-10N, interval 2 K/day) and additional heating alone (black, interval 0.5 K/day)

Average of Heating runs (left), corresponding average of Control runs (right)

Forecast time (ordinate, 1 to 181 days beginning 2 Oct.) vs. longitude (abscissa, in degrees, 60E-240E)



Important points about the additional MJO heating

- Full heating = additional MJO heating + model-generated heating
- Model-generated heating varies across ensemble members (internal variability)
- Additional MJO heating fairly small compared with the total heating (about an order of magnitude less)

Additional MJO heating ~ 0 – 1.5 K/day
Ensemble average of total heating ~ 0 – 15 K/day
(at 500 hPa, averaged 10S – 10N)

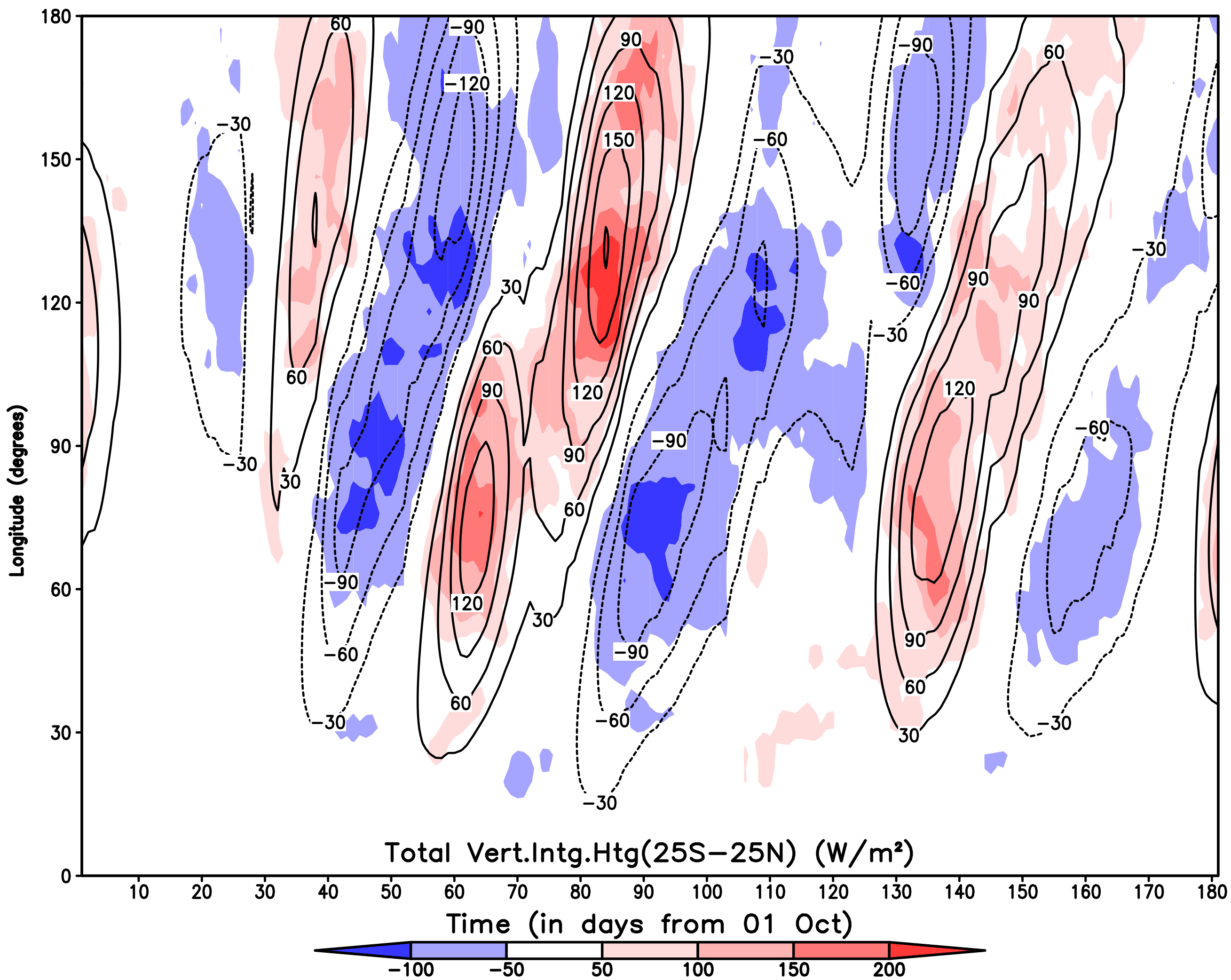
How to extract the "mechanistic mode"?

Added heating is identical for each calendar date and simulation: which mode is similarly common for all simulations?

Predictable Component Analysis

- Also called "Signal-to-Noise Optimizing EOFs"
- Expand any field as a linear combination of "modes", each with its own pattern
- Expansion coefficients (variates) depend on time and ensemble member (year)
- Maximize the "signal"/ "noise" ratio of the variates
- "Signal" = variance of ensemble means
- "Noise" = variance of deviations about ensemble means

- Modes ordered by signal-to-noise ratio (measured by F-value)



Ensemble average vertically integrated diabatic heating anomalies due to all processes, including the additional heating, averaged 25S-25N, shown in shading in W/m^2. Contours show the planetary wave component **reconstructed from the leading two optimal modes**, averaged 25S-25N.

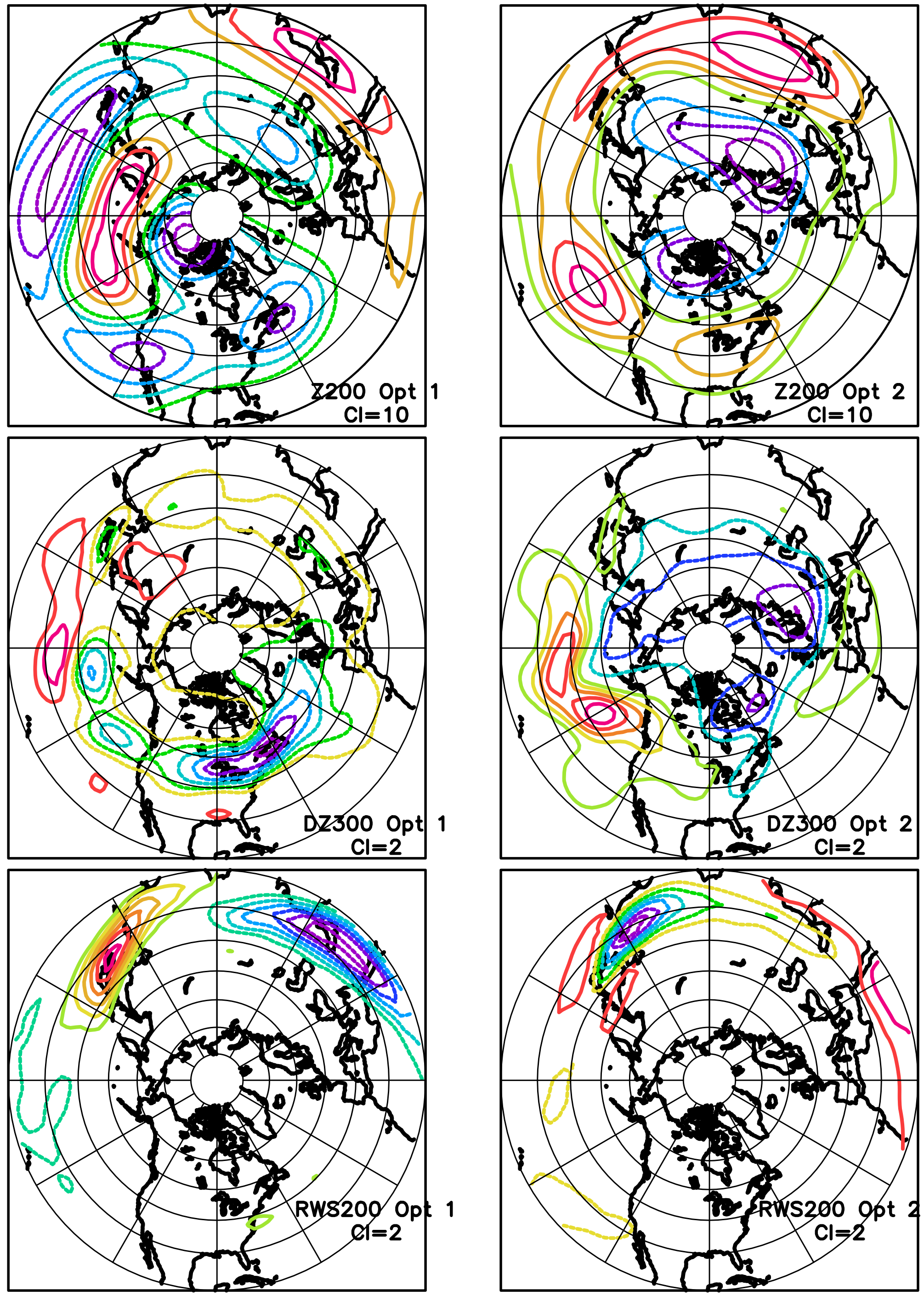
Patterns of two most predictable (optimal) modes for:

200 hPa geopotential height (top row)

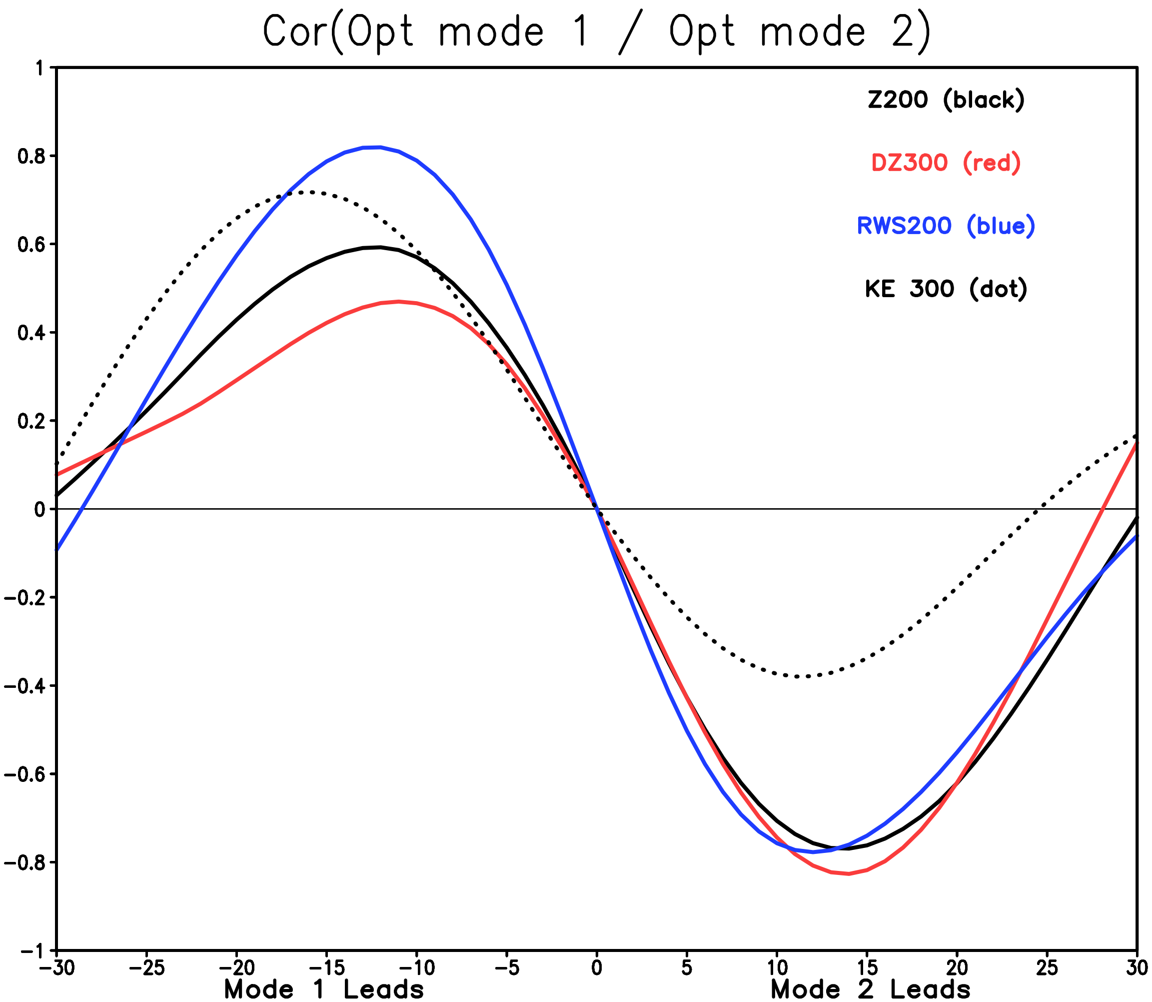
300 hPa synoptic wave geopotential height tendency (middle row)

200 hPa Rossby wave source (lower row)

Contour intervals are:
10 m (upper)
2 m/d (middle)
2 x 10^{-11} s^{-2} (bottom)

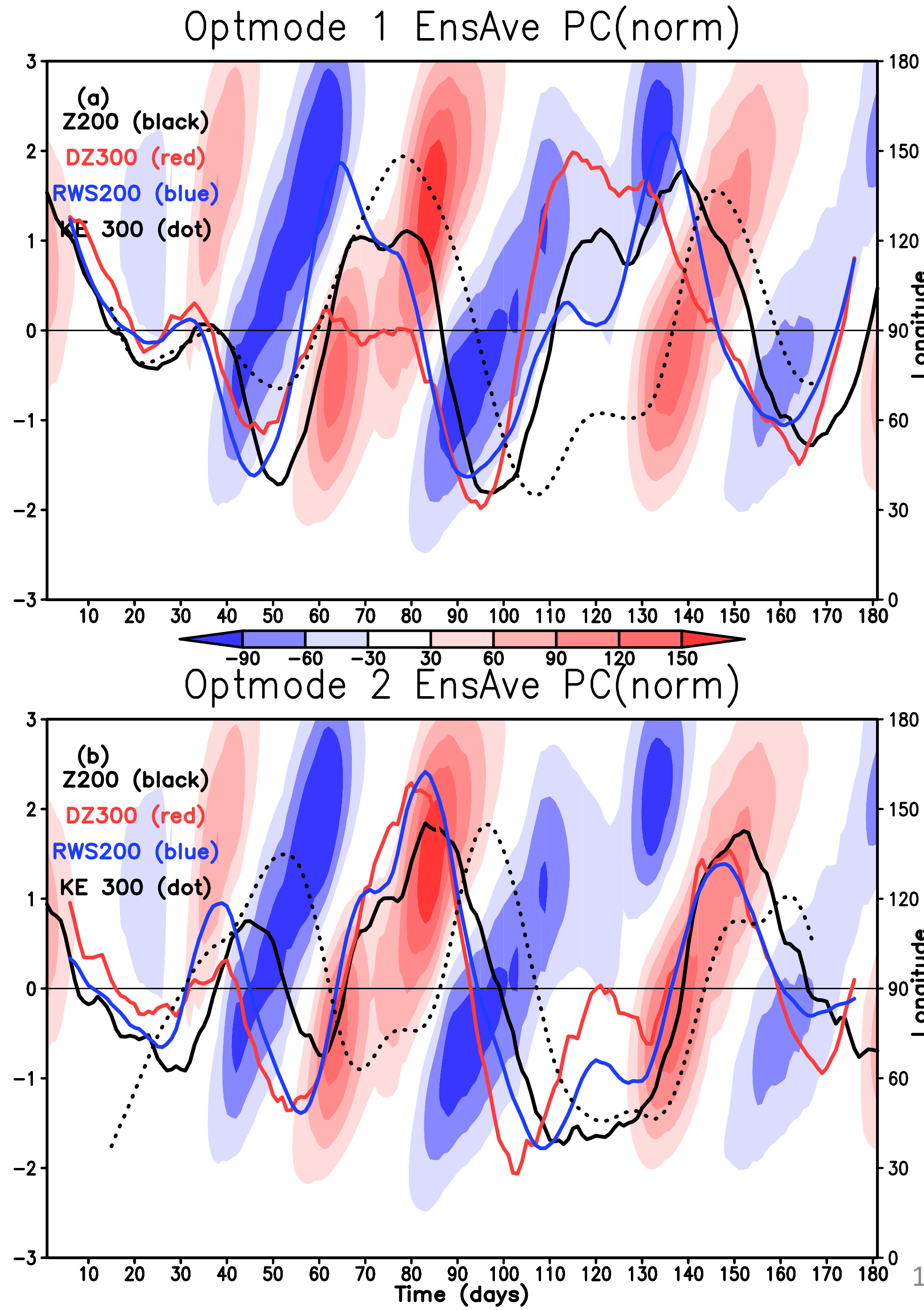


Each mode represents an oscillation of about 30 days

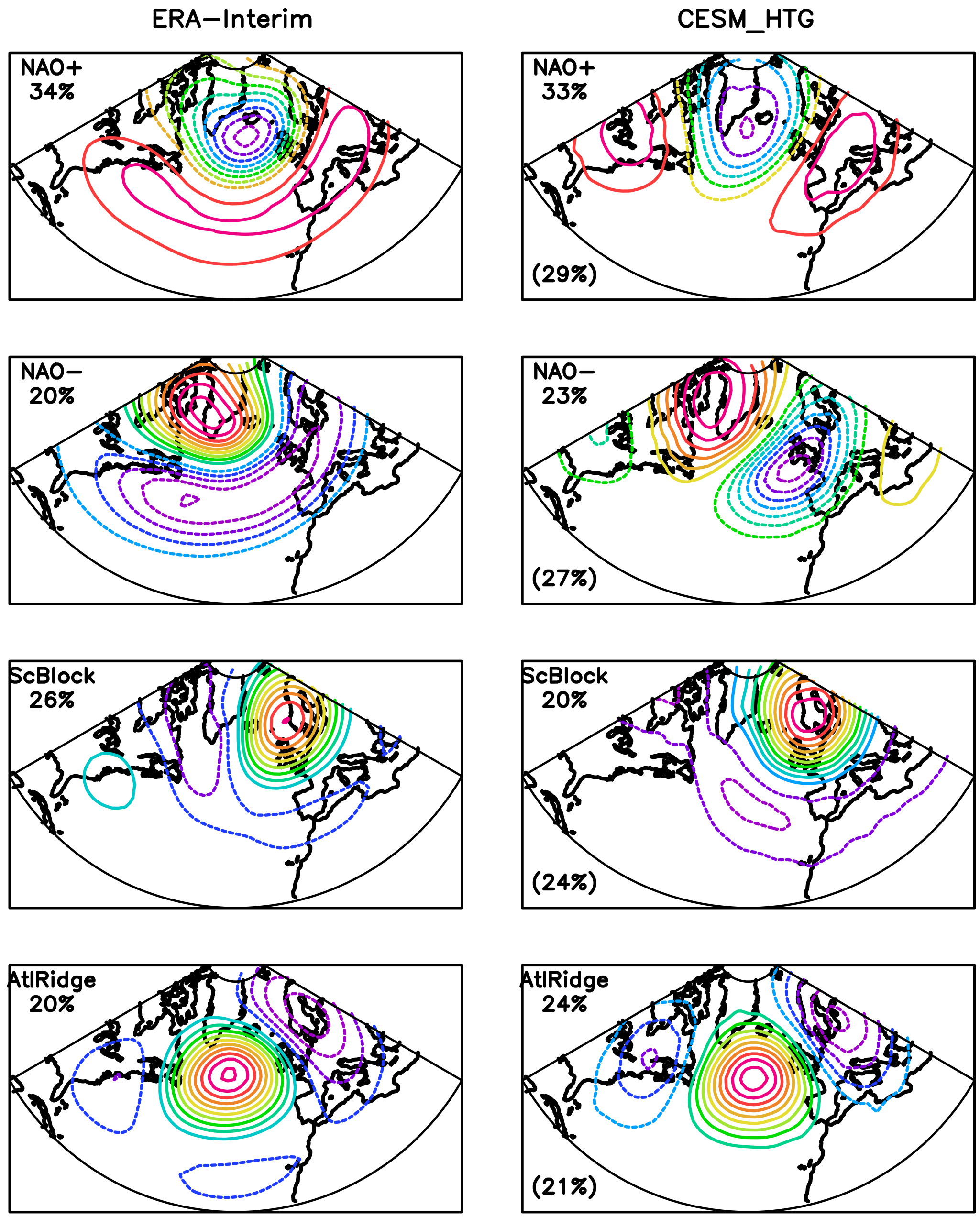


Lag correlation between the two most predictable (optimal) modes for **200 hPa geopotential height** (black), **300 hPa synoptic wave geopotential height tendency** (red), **200 hPa Rossby wave source** (blue). and 300 hPa envelope of transient kinetic energy (dotted line).

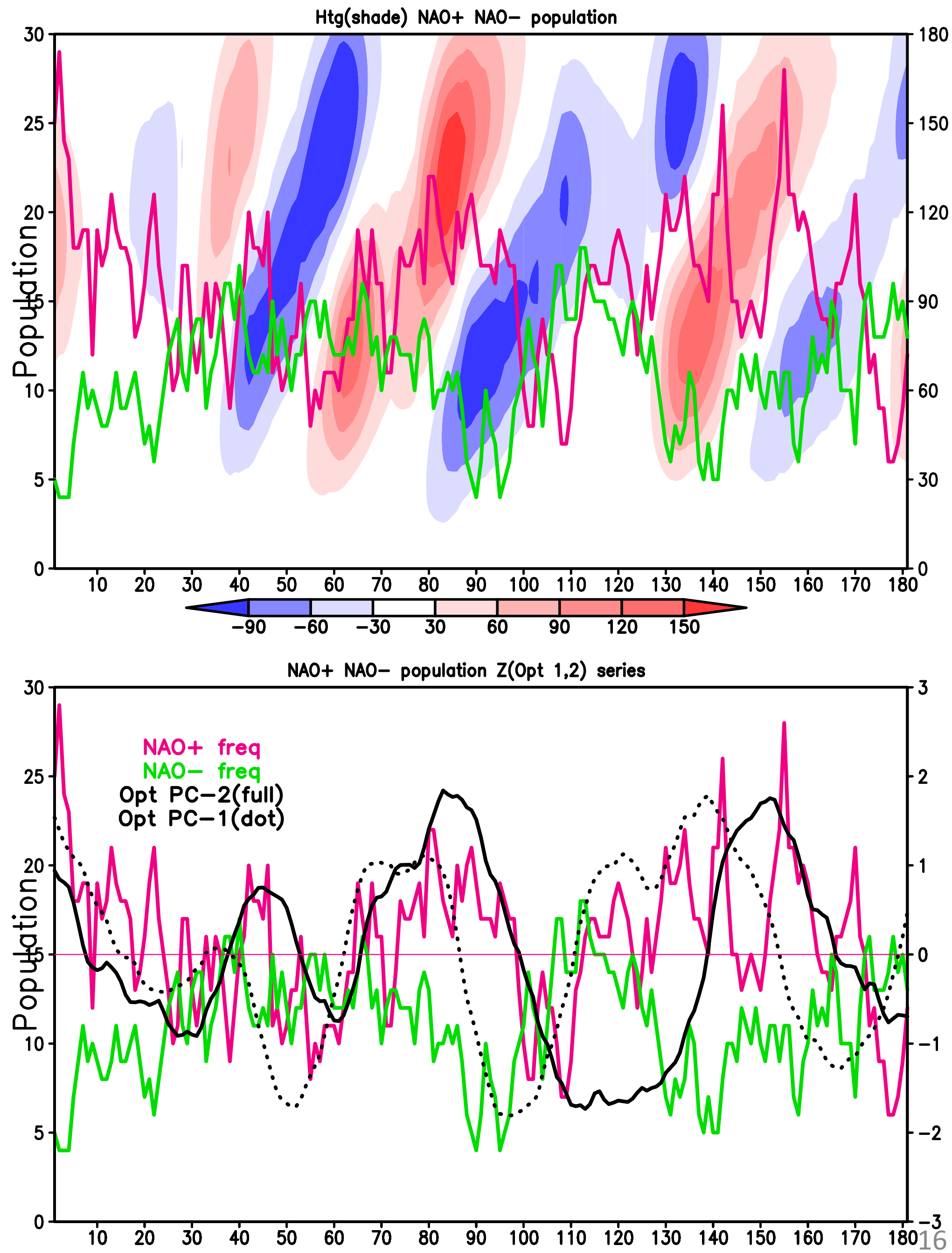
Time series of optimal modes for 200 hPa height (black curve), 300 hPa synoptic wave height tendency (red curve), Rossby wave source (blue curve) and envelope transient kinetic energy (dotted line). Mode 1 (2) given in upper (lower) panel. Time series have unit variance. The shaded field, identical in the two panels, is the planetary wave vertically integrated heating synthesized from the leading two optimal modes, averaged between 25S-25N, Abscissa is time (1 to 181 days), with day 1 corresponding to 02 October. Left ordinate refers to the time series. Right ordinate is longitude, from 0 to 180 degrees.



Composites of 500 hPa height (Z500) for days in which the circulation is assigned to one of four clusters. Results from the ERA-Interim reanalysis (winters 1980/81 - 2011/12) are given in the left-hand column, those for the heating simulations in the right-hand column. Designations of the four clusters, as well as the percentage frequency of occurrence, is given in the upper left of each panel. In the right-hand panel, the corresponding frequency of occurrence for the control simulations is given in the lower left of each panel, in parenthesis. The contour interval is 20 m



Number of occurrences of NAO+ regime (red curve) and NAO- regime (green curve) in all ensemble members, as a function of day (see left-hand scale). Shading in top panels is the vertically integrated planetary wave diabatic heating synthesized from the leading two most predictable modes, in W/m^2(see color bar) as a function of longitude (see right hand scale). Dotted (solid) curve in bottom pan is the ensemble averaged time series of the first (second) most predictable mode (see right hand scale). Time series are normalized to unit variance.



Conclusions

- The MJO cycle of heating and cooling leads to a systematic cycle of forced response in the PNA region
- The cycle of response in the Atlantic is mediated by high-frequency barotropic transients
- The MJO has an impact on the frequency of occurrence of NAO clusters

Some Unanswered Questions

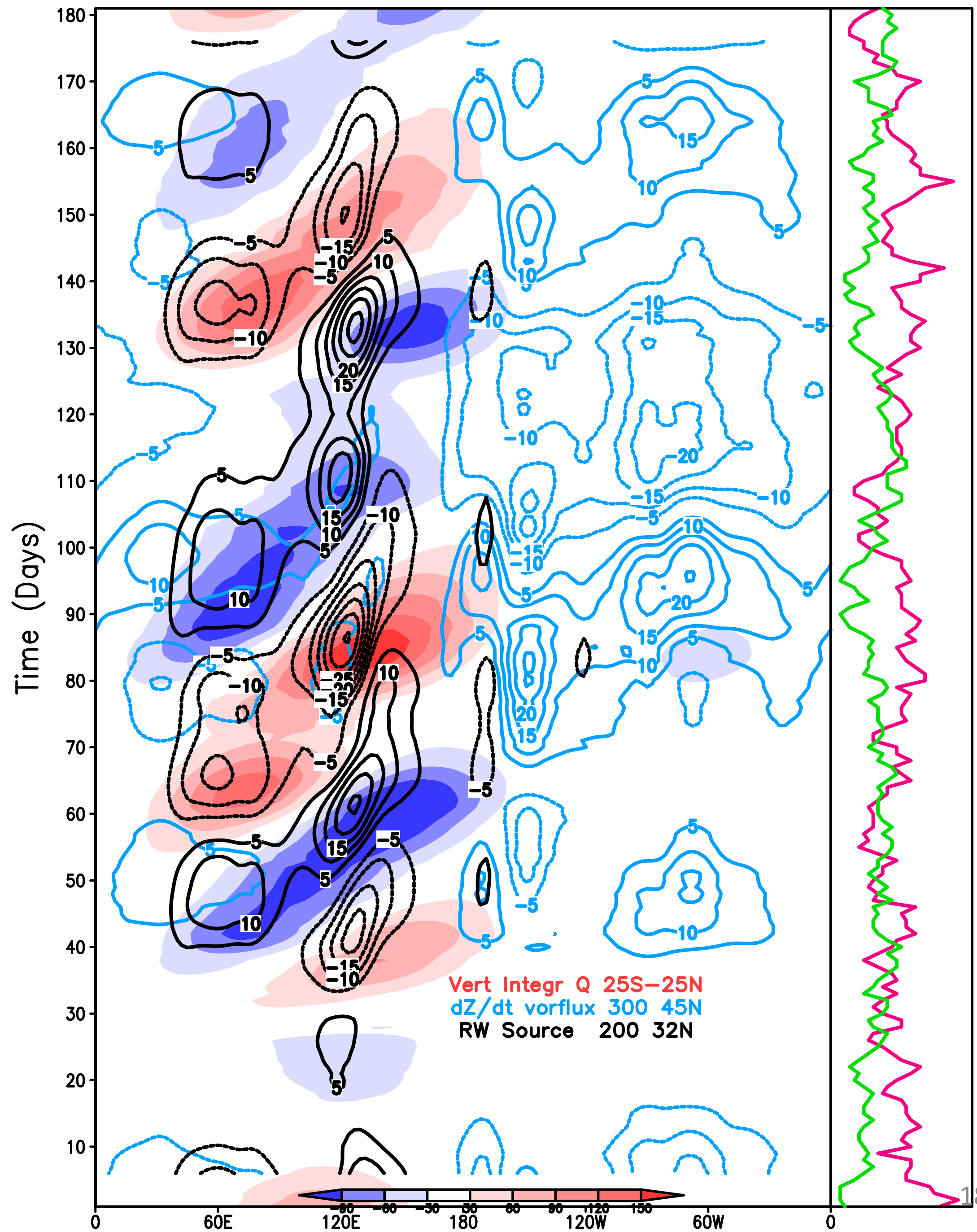
- What is the role barotropic instability? Does it contribute to the signal or the "noise"
- Does the signal to noise ratio depend dramatically on the model used?
- To what extent would a "very good" prediction of MJO tropical convection 2-4 weeks in advance be associated with dramatically improved extra-tropical predictions? (i.e. what is the signal-to-noise ratio in nature?)

Synthesis of leading two most predictable components for: - - **RWS200** at 32N (**black contours**, interval of $5 \times 10^{-11}\ s^{-1}$

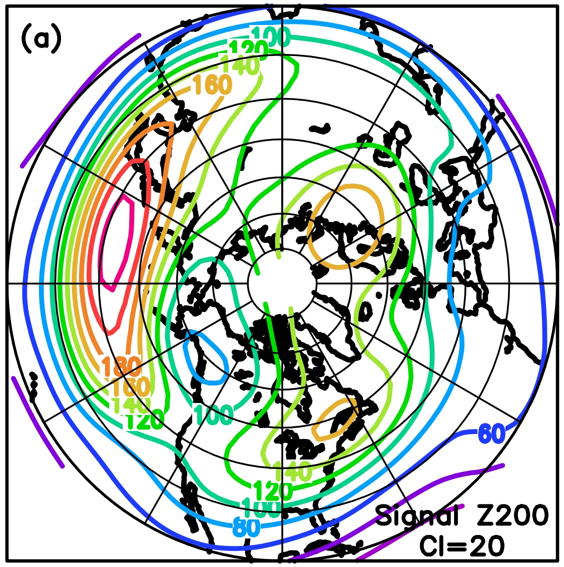
300 hPa Z tendency from synoptic scale vorticity flux at 45 N (**blue contours**, interval 5 m/d

Vertically integrated diabatic heating (averaged 25 S - 25 N) in W m^{-2}.

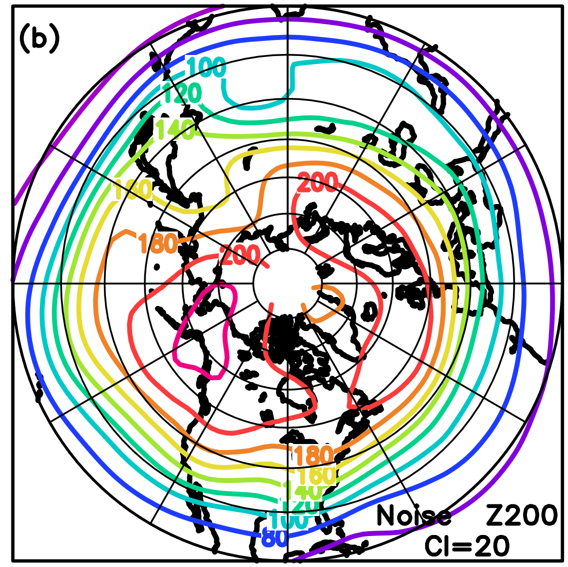
Red (**green**) curves on right show *frequency of occurrence* of **NAO+** (**NAO-**) clusters (set text for details). Abscissa is longitude, ordinate in time in days



Signal



Noise



(a) Signal of 200 hPa height, given as the square root of the variance of daily ensemble means . (b) Square root of the mean daily intra-ensemble variance. Contour interval = 20 m. Grid lines drawn every 10 degrees in latitude from 20N to 80N

Role of transients diagnosed via high-frequency vorticity flux convergence

$$\frac{\partial z}{\partial t} = \frac{f}{g}\frac{\partial \psi}{\partial t} = \frac{f}{g}\nabla^{-2}\left(-\vec{\nabla} \bullet \left(\overline{v'\zeta'}\right)\right)$$

$$\zeta = \nabla^2 \psi$$

(primes denote 2-10 day time scale filtered fields)

Encompasses both

- Extraction of kinetic energy from the mean flow (as in slow barotropic instability modes of SWB)
- Effects of the corresponding momentum fluxes in forcing the jets (Rossby wave breaking)

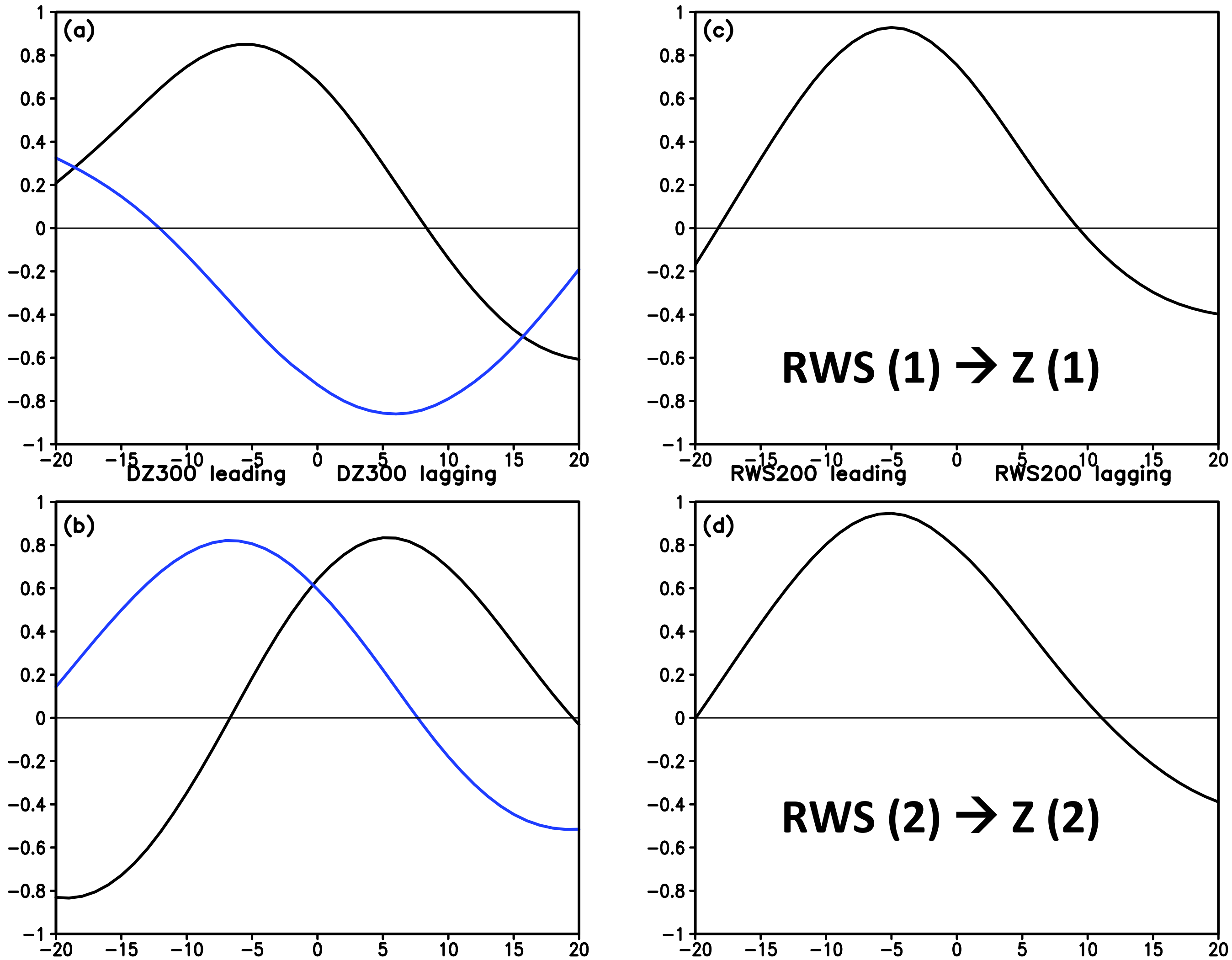
Mode 1 (2) Z200 with DZ300 mode 1

Mode 1 RWS200 with DZ300 mode 1

DZ (1) → Z (1)

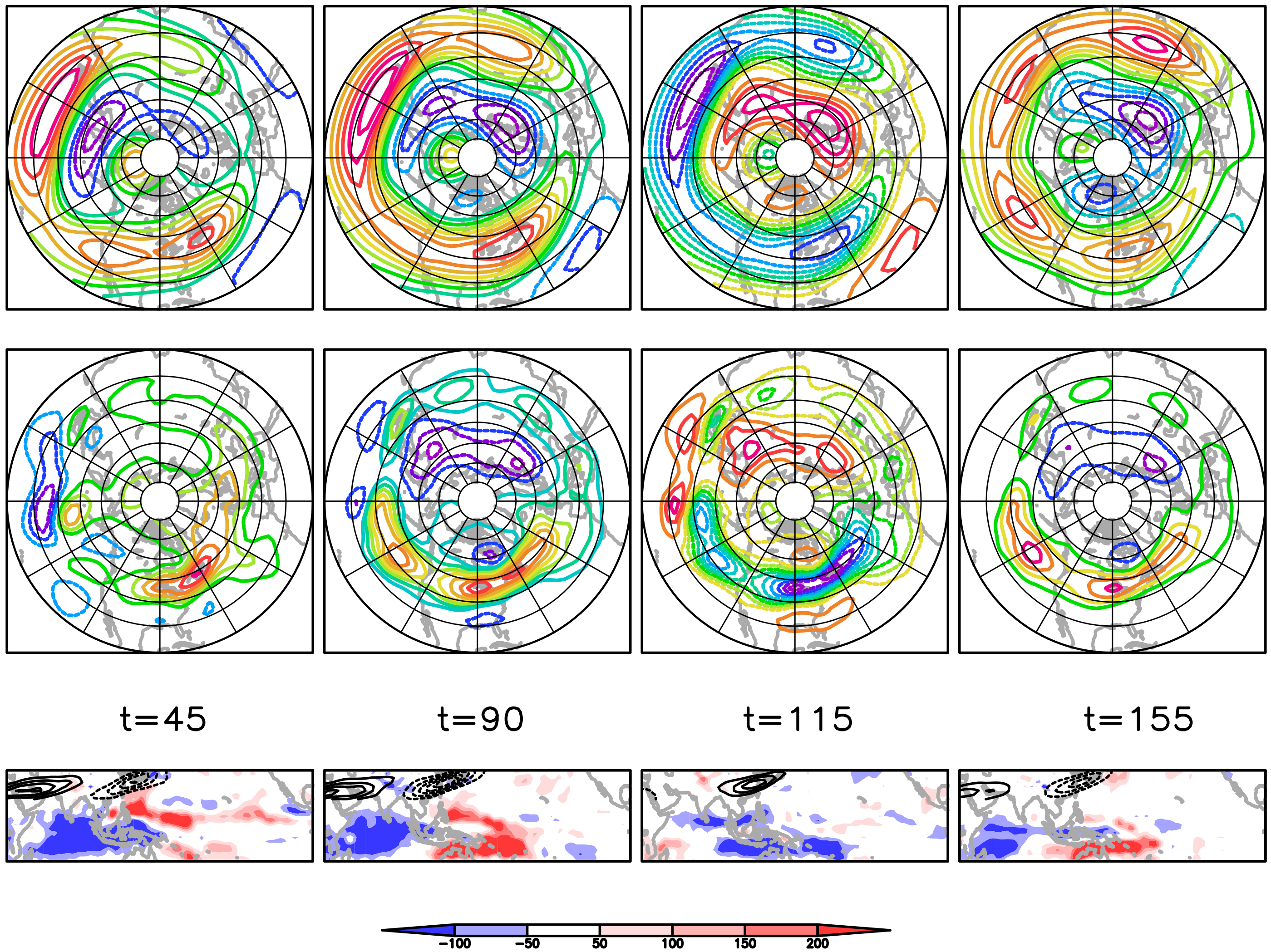
DZ (2) → Z (2)

Z (2) → DZ(1)



Mode 1 (2) Z200 with DZ300 mode 2

Mode 2 RWS200 with DZ300 mode 2



Synthesis of leading two most predictable components at selected times for Z200 (top row), 300 hPa height tendency from synoptic scale vorticity flux (middle row), and 200 hPa Rossby wave source (contours) and ensemble averaged diabatic heating (shaded), bottom row. Contour is 10 m for Z200, 2.5 m/d for height tendency, and 5 x10^{-11} s^{-1} for Rossby wave source.